JWST/MIRI coronographic performances as measured on-sky

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ABSTRACT

Context. Characterization of directly imaged exoplanets is one of the most eagerly anticipated science functions of the James Webb Space Telescope. MIRI, the mid-IR instrument, has the capability to provide unique spatially resolved photometric data points in a spectral range never before achieved for such objects.

Aims. We aim to present the very first on-sky contrast measurements of the MIRI coronagraphs. In addition to a classical Lyot coronagraph at the longest wavelength, this observing mode implements the concept of the four-quadrant phase mask for the very first time in a space telescope.

Methods. We observed single stars together with a series of reference stars to measure raw contrasts as they are delivered on the detector, as well as reference-subtracted contrasts.

Results. The MIRI coronagraphs achieve raw contrasts better than $10^{-3}$ at the smallest angular separations (within 1") and about $10^{-5}$ farther out (beyond 5 ~ 6"). Subtracting the residual diffracted light left behind the coronagraph has the potential to bring the final contrast down to the background- and detector-limited noise floor at most angular separations (a few times $10^{-7}$ at less than 1"").

Conclusions. The MIRI coronagraphs behave as expected from simulations. In particular, the raw contrasts for all four coronagraphs are fully consistent with the diffractive model. Contrasts obtained by subtracting reference stars also meet expectations and are fully demonstrated for two four-quadrant phase masks (F1065C and F1140C). The worst contrast, measured at F1550C, is very likely due to a variation in the phase aberrations at the primary mirror during the observations, and not an issue with the coronagraph itself. We did not perform reference star subtraction with the Lyot mask at F2300C, but we anticipate that it would bring the contrast down to the noise floor.

Key words. Exoplanets – Techniques: image processing – Techniques: high angular resolution

1. Introduction

Exoplanet characterization is entering a new era with the James Webb Space Telescope (JWST), in particular with the coronagraphs of the mid-IR instrument MIRI (Rieke et al. 2015; Wright et al. 2015), designed to obtain high contrast imaging of exoplanetary systems at mid-IR wavelengths. To date, several exoplanets have been directly imaged at mid-IR, mostly from the ground with adaptive optics facilities, but no observations have been obtained beyond ~ 5 µm (with the exception of a candidate detection around α Cen by Wagner et al. 2021). The few observations performed with ground-based instruments at the M band are strongly affected by lower sensitivity due to the sky brightness and variability (Stolker et al. 2020).

The MIRI coronagraphic mode is a suite of four focal plane masks (permanently mounted in the imager field of view), each paired with a dedicated filter and an optimized Lyot stop. They were designed to offer large contrasts and, importantly, small inner working angles (IWAs)1 at mid-IR. Despite longer operating wavelengths than NIRCAM (the near-IR instrument of James Webb), the MIRI coronagraphs deliver similar IWAs (~ 0.33") at F1065C. Three of these coronagraphs use four-quadrant phase masks (4QPMs; Rouan et al. 2000), manufactured with reactive ion etching in a germanium substrate. Details about the 4QPM manufacturing for MIRI can be found in Baudoz et al. (2006). Since the 4QPMs are chromatic, they are used in conjunction with the narrowband filters F1065C ($\lambda_0 = 10.575\mu$m, $\Delta \lambda = 0.75\mu$m), F1140C ($\lambda_0 = 11.30\mu$m, $\Delta \lambda = 0.8\mu$m), and F1550C ($\lambda_0 = 15.50\mu$m, $\Delta \lambda = 2.5\mu$m).

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1 The IWA, although sometimes ill defined, is the angular separation at which an off-axis point source will have its transmission reduced to 50%.
The central wavelengths of the filters were chosen to characterize the atmospheres of directly imaged, young giant exoplanets, essentially to complement near-IR photometric and spectroscopic measurements. The F1065C and F1140C filters are meant to provide photometric measurements of exoplanets in and out of the ammonia absorption band. The F1550C filter, in combination with F1140C, is important for constraining models of the thermal balance of the planet and of the behavior of any atmosphere. The detection performance was first estimated in Boccaletti et al. (2015), and Table 1 summarizes the available configurations.

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for a photometric reference, as well as to provide a sufficient
flux level compatible with the sensitivity at each filter when the
star is on-axis, and hence masked and attenuated by the coron-
agraph (attenuation on-axis can be as large as a factor of ~400
as measured in F1550C). We ended up with two series of ob-
jects, one set optimized for F1065C and F1140C and the other
for F1550C and F2300C. The targets are: HD 158165 (K=4.07),
of which the flux densities are 0.550 Jy and 0.450 Jy for, re-
spectively, F1065C and F1140C; and HD 163113 (K

Table 3. Three input cases used to simulate the performance of the MIRI coronagraphs. Wavefront errors (OPD) are provided in nanometers RMS from the telescope, the instrument MIRI, the frill around the primary mirror, the ISIM electronics compartment (IEC), and thermal distortion (TD), respectively. TA and jitter are given in milliarcsec per axis, and the shear is given as a percentage of the telescope pupil.

<table>
<thead>
<tr>
<th>OPD tel.</th>
<th>OPD MIRI</th>
<th>OPD Frill</th>
<th>OPD IEC</th>
<th>OPD TD</th>
<th>TA [mas/axis]</th>
<th>jitter [mas/axis]</th>
<th>pupil shear [%]</th>
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</thead>
<tbody>
<tr>
<td>best</td>
<td>73</td>
<td>32</td>
<td>0.017</td>
<td>1.6</td>
<td>0.016</td>
<td>6.25</td>
<td>2.5</td>
</tr>
<tr>
<td>nominal</td>
<td>73</td>
<td>32</td>
<td>0.07</td>
<td>2.8</td>
<td>0.07</td>
<td>8.76</td>
<td>3.8</td>
</tr>
<tr>
<td>requirement</td>
<td>73</td>
<td>32</td>
<td>1.75</td>
<td>4.6</td>
<td>1.67</td>
<td>12.51</td>
<td>5.8</td>
</tr>
</tbody>
</table>

HD 162989 is at 1.16° from the target. No reference star was
observed for the Lyot coronagraph.

Figure 1 shows images of each of the coronagraphic fields
when observing the background sky. All four show an unex-
pected stray light feature, known familiarly as “glow sticks,”
which appear as increased signal along the structural edges in
the MIRI imager entrance focal plane. They are most apparent
across the center of the F1550C image, where light is being
scattered into the “science” optical path by the raised edge of
the phase boundary. In the F2300C image, the bright glow stick
marks scattering at the lower edge of the aluminium Lyot apen-
ture. The stray light is visible, but fainter, for the shorter wave-
lengt 4QPM coronagraphs in Fig. 1. Stray light is also seen
along the upper edge of the Lyot spot.

Two key observations were important in determining the root
cause of the glow sticks. First, their shape and brightness were
independent of the observatory pointing direction to within a few
percent, ruling out an astronomical origin. Second, photomet-
ric analysis of the glow sticks determined that the illuminating
source was well fitted by a gray body spectrum with an effective
temperature of 120 ± 20 K, characteristic of the region where the
sunshield approaches the deployable tower assembly (Lightsey
et al. 2012). Nonsequential optical path analysis (S. Rohrbach,
private comm.) has used the pre-launch solid model of the ob-
servatory plus MIRI to identify a path from this warm region of
the sunshield to the MIRI entrance focal plane, via a reflection
from the secondary mirror (SM), followed by scattering from the
hinged SM support strut. The model reproduces features similar
to the glow sticks by modeling the scattering process at the me-
chanical edges of the phase masks and Lyot stop. The agreement
is not yet perfect: the model produces glow sticks along both the
vertical and horizontal nulling axes of the phase masks, whereas
we only observe features in the horizontal (along row) direction
in our data. We ascribe this discrepancy to a lack of fidelity be-
tween the pre-launch solid model and the as-flown hardware.
To mitigate the glow stick effect (which could be brighter than the observed source itself), it is necessary to subtract a background image obtained in the same filter and for an identical exposure time until the variability of this pattern is understood and an alternative approach is proposed. If this procedure is followed, the effect of the glow sticks on the final data is completely removed, except for the expected modest increase in photon noise at their positions. At the moment, this step is not automatically included in the observing sequence, nor in the reduction pipeline.

To precisely center the star on the coronagraph axis, we need both a sub-pixel estimation of the coronagraph position and a precise target acquisition (TA) procedure (Cavarro et al. 2008b). The glow sticks prevented us from using the dark transitions of the 4QPMs to estimate the coronagraph center, which had been the plan. Instead, we developed a method based on comparison with a diffraction model after subtracting the glow sticks out, to be presented in a separate paper (Baudouz et al., in prep.). These measurements were used in the TA procedure to reach a pointing accuracy of about 5 to 10 mas, in full agreement with the requirement (Rigby et al. 2022).

3. Simulations

The simulations presented in Boccaletti et al. (2015) were recently reassessed by the JWST Coronagraph Sensitivity Working Group to incorporate the up-to-date telescope and instrument parameters. We assumed a temporal sampling of $\pi/5 \approx 0.63$ minutes per frame, for a total sequence of about 56 minutes on the target (90 frames) followed by the same amount of telescope time on a reference star, which is dithered on nine positions ($9 \times 10$ frames, i.e., each dither position has a total of one-ninth the exposure time as the target source.). This so-called small grid dither (SGD; Soummer et al. 2014; Lajoie et al. 2016) allows a diversity in the observations of the reference star to further reduce the starlight, making use, for instance, of principal component analysis (PCA; Soummer et al. 2012). The SGD is a square grid with 10 mas steps. Although the error on the positioning of the star onto this grid is estimated to be 1 or 2 mas, this has no effect on the estimation of the starlight, which only relies on the variations in the intensity of speckles around the mask center, not on absolute knowledge of the pointing.

Static aberrations include the telescope wavefront aberration as measured in the early phase of commissioning (73 nm RMS) and the MIRI instrument aberrations measured on the ground (32 nm RMS). The former wavefront map is made of mid spatial frequencies and is expected to evolve over the life of the mission, while the latter contains mostly low spatial frequencies. Additional dynamical components in the wavefront on a $1 \sim 2$ hour timescale are also taken into account with various spatial and temporal frequencies, such as the thermal distortion of the telescope backplane, the fast oscillation in the heaters in the Integrated Science Instruments Module (ISIM) electronics compartment, and the frill around the primary mirror designed to stop the stray light, all being relatively small in terms of wavefront errors for an instrument such as MIRI (Table 3).

In addition, the simulation accounts for misalignments at the focal plane and pupil plane in the coronagraph. First of all, the offset between the star’s position and the center of the mask corresponds to the TA error. For convenience, in the simulations the target star is perfectly centered while the reference star is offset by this TA error. Then, we included line of sight jitter that is the motion of the star’s position during the observation. Moreover, the Lyot stop, located at the MIRI filter wheel, can be slightly misaligned with the telescope pupil. This error is expressed as a percentage of the telescope pupil diameter, assuming a shear along the diagonal. Three distinct scenarios were considered: “best,” “nominal,” and “requirement.” The values for all parameters of the simulations are provided in Table 3. Finally, we included a spectral shift of 3% of the F1140C filter with respect to the operating wavelength of the corresponding 4QPM, which caused a chromatic leakage in the images visible as a central peak in the coronagraphic image.

The simulations are time averaged, so we are left with one single image for the target and nine for the reference. We applied PCA using nine components to build a reference frame and then subtracted this out from the target image. We provide a comparison of the PSF images (off-axis) and coronagraphic images (on-axis) observed during commissioning to simulated images in Figs. 2 and 3, respectively. They are virtually identical, and the surrounding field on the observed image is very clean, with no evidence of residual latent images.

4. Measured contrasts

The data were processed with the dedicated JWST pipeline up to stage 1, which involved detector-level corrections (calwebb_detector1; see JWST pipeline documentation) and produced level 2a count-rate data, but without flat field correction (not available at the time of commissioning), nor background subtraction. Then we used our own specific procedures for subtracting the background and reference star images. There was no further treatment to remove the glow stick effect other than background subtraction. Contrasts were measured azimuthally as a function of the angular separations first in the raw coronagraphic image (azimuthal mean), and then with the subtraction of a reference image (azimuthal standard deviation). We warn the reader that the contrast curves presented here are meant for comparison with simulated data and to demonstrate the capacity of the MIRI coronagraphs, and it would be overly optimistic to use them to assess the detectability of exoplanets, which would require accounting for the coronagraph’s field transmission as well as the contrast definition proposed in Mawet et al. (2014). The reference-subtracted image was created either by subtracting a single reference exposure from the target exposure (one-to-one subtraction) or by subtracting an image constructed from a combination of multiple reference exposures (PCA subtraction). In commissioning, we used the SGD mode for both the target and the reference, so we have nine images for each, which means 81 possible one-to-one subtractions and nine PCA subtractions. We only display the resulting contrast curve that takes the best value of the contrasts for each separation independently (consistent with the best subtraction producing the largest contrast at all separations). Examples of the subtracted images for the three 4QPMs are given in Fig. 4. The measurements are compared to the noiseless simulated contrasts for the three scenarios mentioned in Sect. 3, and to the Exposure Time Calculator (ETC) estimations using the actual flux of the observed stars and exposure times, together with a “medium background” configuration. The ETC assumes that the reference star subtraction is limited by photon and detector noises and so does not capture a possible variability in the optical wavefront aberrations or pointing.

Figure 5 displays the contrast curves for all four coronagraphic filters. The raw contrasts (brown lines) are in good agreement with the simulations of the 4QPMs coronagraphs. The F1065C and F1550C show the characteristic dip in the center, while the central region with F1140C is clearly affected by the
chromatic leakage. Raw contrasts are usually better than $\sim 10^{-3}$ and reach the background limit at $\sim 10^{-5}$ (beyond 6″ or so). The one-to-one subtraction (orange lines) only provides a small gain with respect to the residual diffraction left behind the coronagraph, while PCA (red lines) offers a more substantial attenuation, reaching the background floor at all angular separations in F1065C and F1140C, which is in line with ETC expectations (green lines). The two references (REF1 and REF2 in Fig. 6) observed in F1140C back-to-back with the target produce very comparable contrast limits (dotted red line), indicating a small
Fig. 4. One-to-one (top) versus PCA (bottom) subtraction of coronagraphic images (TARG and REF1) in the three 4QPM filters. Several background sources (either positive or negative) are observed around the target and reference stars. The pixel scale is 110 mas.

Fig. 5. Measured raw and 3σ reference-star-subtracted contrasts for all MIRI coronagraphic filters as compared to the simulations and to the ETC prediction. Subtracted contrasts are shown for the one-to-one and PCA algorithms. Reference stars were not observed at F2300C.
obtained after mirror re-phasing, leading to a reduced amount of aberrations on the primary mirror, while the second epoch of REF1 was obtained with approximately 86 nm RMS of aberrations in to-tal paraxial wavefronts. The first part of the F1140C obser-vation C3, causing a significant departure of the wavefront with respect to the initial state. The first part of the F1140C obser-vations (TARG, REF1, and REF2) were observed in this con-figuration with approximately 86 nm RMS of aberrations in to-tal on the primary mirror, while the second epoch of REF1 was obtained after mirror re-phasing, leading to a reduced amount of 65 nm RMS aberrations. Such a difference is not visible in the raw coronagraphic images when comparing the two epochs. However, the reference-star-subtracted contrast in PCA if using these two epochs is reduced by as much as an order of magnitude at a separation of 0.66'' compared to the case with a single epoch. The overall contrast is affected up to a distance of about 4''. We retrieved the wavefront measurements bracketing these data, assigning the first map to the target and the second to the reference, in order to model the loss of contrast. We obtained almost the same contrast curve as the one measured (blue dotted line compared to red dashed line in Fig. 6), lending credibility to our hypothesis.

Overall, for F1065C and F1140C, PCA subtraction using reference stars achieves a contrast of 2 to 4.10^{-5} inside 1''. This is compatible with the best case scenario in the noiseless simulation, showcasing the very good performance met by the observatory in terms of pointing, repeatability, and stability. In fact, we estimate that the main parameters defining the reference-star-subtracted contrast are even better than the best case, with a line of sight jitter likely in the 1-2 mas range and TA at a level of 5 mas in total. A qualitative comparison with simulated images indicates a pupil shear of about 2-3% (responsible for the strip at ~ 45'' as seen in the coronagraphic images in Fig. 3). This value will be refined for each coronagraph configuration in Baudouz et al. (in prep.).

In the F1150C filter, the raw contrasts are in perfect agree-ment with the simulation, but both the one-to-one and the PCA subtraction are much worse than the ETC or simulated predic-tions. The 3\sigma contrast achieves only ~ 4.10^{-4} at 1'', while we could expect 2.10^{-3}. Since the starlight rejection by the 4QPMs itself is coherent with the model, the only plausible explanation is again a mismatch in terms of wavefront errors between the target and the reference star. In fact, a “tilt event” (change in segment position; see Rigby et al. 2022) on one of the primary mirror segments presumably occurred between June 16 and June 19, 2022, and could be the cause of such a reduced contrast, although the causality cannot be firmly established. The project has committed to making telescope wavefront measurement available on roughly 2-day centers, which could determine if it is plausible that such an event occurred. There is currently no approach for more accurately locating the time of a tilt. With time, building a library of reference star images will certainly help mitigate these issues. We note that the very first science observations at F1150C in Carter et al. (2022) deliver reference-star-subtracted contrast within expectations.

Finally, we obtained a raw contrast measurement with the F2300C Lyot mask. We find that the level of contrast qualitatively matches the model prediction but does not agree perfectly. The discrepancy can be as large as a factor of 2 to 3 between 2'' and 3'' (if we omit distances that are inside the mask and hence irrelevant). The observed image itself features a stronger diffraction in the direction perpendicular to the bar holding the Lyot spot, producing an asymmetrical image in contrast to the simulation (Fig. 3). The reason for this disagreement is still under investigation, but we can confidently assume that, like the other coronagraphs, the Lyot mask performance will be set by the background level when using a reference subtraction. In fact, this is even more the case at F2300C since the background is stronger. Indeed, while the exposure times are similar in F1550C and F2300C, the achievable contrast is ~4 times worse with the Lyot mask (as predicted with ETC).

5. Conclusion

Commissionsing observations were the first opportunity to actu-ally measure the performance of the MIRI coronagraphs in real conditions because high contrast imaging was not practical during the ground testing phase. The pointing accuracy and reproducibility have proved excellent, meeting the specifications of 5 mas at best, and definitely less than 10 mas (one-tenth to one-twentieth of a pixel). All four coronagraphs, the 4QPMs and the Lyot, behave satisfactorily on point sources, in the sense that the coronagraphic images and the raw contrasts are almost identi-cal to the models and meet the contrast specifications. A small difference is found with the Lyot mask, for which an additional diffraction is superimposed on the predicted image, perpendicular to the bar. Calibrating the residual diffraction left unattenuated by the 4QPMs with reference stars brings the contrast to the limit imposed by thermal background and detector noises, at least for the two shortest wavelength filters, F1065C and F1140C. The reference-star-subtracted contrast with the F1550C filter is likely limited by variations in the wavefront errors of the primary mirror, which may have occurred during the observations (a tilt event). Similarly, subtracting images taken a few days apart shows significant deterioration of the contrast due to primary mirror re-phasing between the two epochs. At the moment, it is recommended that each coronagraphic observation with MIRI include: a background image of the same duration as the science exposure, a nine-point SGD on the reference star (the five-point SGD was not tested during commissioning), and an off-axis image of the star for photometric calibration purposes, in agreement with former recommendations in JDoX\(^\text{2}\). Altern-\footnote{1 https://jwst-docs.stsci.edu/ jwst-mid-infrared-instrument/miri-observing-strategies/ miri-coronagraphic-recommended-strategies}

![Fig. 6. Measured 3\sigma reference-star-subtracted contrasts with PCA in the F1140C filter for the single-epoch and two-epoch cases, and compared to the simulation that takes the wavefront error maps (OPD) into account before and after re-phasing of the primary mirror segments.](image-url)
tively, one can use the TA images for photometry, but they are obtained with different filters (usually a neutral density filter).

The commissioning of the MIRI coronagraphs reported here has demonstrated: excellent performance; that the use of the 4QPM technique provides the expected small IWA; and rejection factors and sensitivity in excess of pre-launch expectations. We can therefore anticipate that, with the observing recommendations in this paper, the MIRI coronagraphs will have a key role in the direct imaging of exoplanets to constrain atmospheric properties for the very first time at mid-IR wavelengths, as has already been illustrated with the very first release of an exoplanet image with a MIRI coronagraph by Carter et al. (2022).

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